

SUBSTITUTE SPECIFICATION

MICROWAVE PLASMA PROCESSING METHOD,  
MICROWAVE PLASMA PROCESSING APPARATUS, AND  
5 IT'S PLASMA HEAD

[Field of the Invention]

The present invention relates to a microwave plasma processing method, a microwave processing apparatus and  
- -10 its plasma head, used for the microwave plasma processing of a large type glass substrate for flat panel display (FPD) or a substrate such as a semiconductor wafer.

[Background Art]

For instance, in a microwave plasma CVD processing  
15 apparatus for processing a large type glass substrate for FPD or a substrate such as a semiconductor wafer, it has been practiced in the past in such manner that a batch processing of the sheet-by-sheet type has been carried out and the substrates to be processed by plasma CVD  
20 processing has been passed through a load-lock chamber kept under vacuum condition and the substrates have been brought into or out of a processing chamber maintained similarly under a predetermined vacuum condition. As a result, each time the substrates were brought into or out  
25 of the processing chamber, the processing chamber had to

be evacuated and released to atmosphere.

In particular, when two or more different processing procedures had to be applied on the substrates, each of such processing procedures had to be performed in batch processing procedure with the substrates being transferred through a plurality of isolated spaces (i.e. the processing chamber). For this reason, it was not possible to continuously carry out the CVD processing of the substrates, and expensive vacuum processing means had to be used.

Under such circumstances, a new technique has been developed, in which no such vacuum processing means is required and plasma CVD processing is continuously carried out on in-line basis under the atmospheric pressure (normal pressure). In the new plasma CVD technique under normal pressure, a plasma technique is used, which makes it possible to operate under the atmospheric pressure without using vacuum system, and the substrate to be processed such as a semiconductor wafer is continuously subjected to CVD, etching and ashing processing (Non-Patent Reference 1). Further, in this normal pressure plasma CVD technique, semiconductor wafers are placed on a circulating type wafer transfer unit such as a belt conveyer and different types of processing are carried out on flow production (flow shop)

system by using a plurality of normal pressure plasma systems (Non-Patent Reference 2).

Also, a new plasma processing apparatus (e.g. CVD apparatus) has been proposed (Patented Reference 1), in  
5 which a linear plasma is prepared by using electromagnetic wave, and surface treatment of the object to be processed is performed while relative position between the object to be processed (such as semiconductor wafer) and the plasma is being moved with the surface of  
10 the object to be processed maintained at horizontal position with respect to the linear plasma.

[Non-Patented Reference 1] Motokazu YUASA "Plasma CVD Technique Without Using Vacuum Technique",  
Nikkei Microdevices, January 2001, p.3.

15 [Non-Patented Reference 2] Motokazu YUASA "Plasma Technique Without Using Vacuum Technique",  
Nikkei Microdevices, April 2001; pp.139-146.

[Patented Reference 1] JP-A-2001-93871.

## 20 DISCLOSURE OF THE INVENTION

Although different types of processing can be continuously carried out by the conventional type microwave plasma CVD method and apparatus as described above, there have been problems in: non-uniformity of  
25 microwave at the microwave feeding unit of the plasma

head, incompleteness of processing of gas flow and gas shielding, non-uniformity of plasma density due to the standing wave, abnormal discharge at slots of the plasma head, etc.

5        To solve the problems of the conventional type microwave plasma CVD processing method and processing apparatus as described above, it is an object of the present invention to provide microwave plasma processing method, a microwave plasma processing apparatus, and a  
10   plasma head for such apparatus, by which it is possible to generate linear high-density plasma by using high-density microwave source, and different types of film-deposition processing can be continuously performed.

      According to the microwave plasma processing method,  
15   the microwave plasma processing apparatus and the plasma head of the present invention, linear plasma is generated by microwave, and an object to be processed is processed under the atmospheric pressure or under a pressure near the atmospheric pressure while the object to be processed  
20   is being moved by maintaining the surface of the object to be processed at horizontal position with respect to the linear plasma. An H-plane slot antenna is provided on the plasma head. Slots of the H-plane slot antenna are arranged alternately on both sides of the centerline  
25   of the waveguide at a pitch of  $\lambda g/2$ , and a uniforming

line is arranged with a distance from said slot to the emission end of the plasma head being set to  $n \cdot \lambda_g/2$  where the symbol  $\lambda_g$  represents guide wavelength of microwave.

5        Also, according to the microwave plasma processing method, the microwave plasma processing apparatus and the plasma head of the present invention, linear plasma is generated by microwave, and an object to be processed is processed under the atmospheric pressure or under a  
10       pressure near the atmospheric pressure while the object to be processed is being moved by maintaining the surface of the object to be processed at horizontal position with respect to the linear plasma. An E-plane slot antenna is provided on the plasma head. Slots of the E-plane slot  
15       antenna are arranged along the centerline of the waveguide at a pitch of  $\lambda_g$ , and a uniforming line is arranged with a distance from said slot to the emission end of the plasma head being set to  $n \cdot \lambda_g/2$  where the symbol  $\lambda_g$  represents guide wavelength of microwave.

20       Further, according to the microwave plasma processing method, the microwave plasma processing apparatus and the plasma head of the present invention, a uniforming line is provided on the plasma head under similar processing conditions, and the uniforming line is made of a material  
25       with high dielectric constant. Also, the uniforming line

is made of quartz, and its end portion is extended by  $1/4$   
 $\lambda$ . Also, an electromagnetic wave absorbing material with  
high dielectric loss is attached on end portion of the  
uniforming line to reduce the standing wave on the plasma  
5 head where the symbol  $\lambda$  represents free space wavelength  
of quartz.

Also, according to the microwave plasma processing  
method, the microwave plasma processing apparatus and the  
plasma head of the present invention, it is designed in  
10 such manner that a film-deposition gas is passed by down-  
flowing through a film-deposition gas feeding nozzle  
provided on the plasma head under similar processing  
conditions, and also, that a film-deposition gas is  
passed by side-flowing through the film-deposition gas  
15 feeding nozzle.

Further, according to the microwave plasma processing  
method, the microwave plasma processing apparatus and the  
plasma head of the present invention, a feeding pipe for  
feeding a shield gas into the plasma head is connected,  
20 and by a buffer plate the shield gas is uniformly  
supplied into the plasma processing chamber downstream of  
the shield gas feeding pipe. Also, a buffer plate for  
carrying out uniform exhaust of the gas is provided on  
exhaust side. A pressure  $P_1$  in the plasma processing  
25 chamber is set to a value lower than a pressure  $P_3$  on the

outermost periphery of the plasma head, and the pressure  $P_3$  is set to a value lower than a pressure  $P_2$  near the buffer plate for performing uniform exhaust, thus preventing the leakage of the gas from the plasma head.

5        According to the microwave plasma processing method, the microwave plasma processing apparatus and the plasma head of the present invention, linear high-density plasma is generated from the plasma head by using a high-density microwave source. As a result, it is possible to perform  
10    continuous CVD processing with high accuracy. Different types of plasma sources are aligned in transporting direction of the substrate to be processed by film-deposition processing. As a result, different types of continuous film deposition can be carried out.

15        Further, according to the microwave plasma processing method, the microwave plasma processing apparatus and the plasma head, and a uniforming line of the plasma head of the present invention, by setting optimal condition of the basic dimensions and by eliminating the standing wave,  
20    more uniform microwave can be emitted through the slit of the plasma head. Also, homogeneity of the film deposition gas can be maintained because of down-flowing and side-flowing of the gas, and this contributes to the improvement of the film deposition rate.

25        Also, remarkable effects can be provided for gas

shielding of the film deposition gas with very high accuracy.

#### BRIEF DESCRIPTION OF THE DRAWINGS

5        Fig. 1 is a front view to show schematical arrangement of a microwave plasma CVD apparatus according to an embodiment of the present invention;

      Fig. 2 is a plan view of the microwave plasma CVD apparatus shown in Fig. 1;

10       Fig. 3 is a perspective view of three plasma heads to be used in the microwave plasma CVD apparatus shown in Fig. 1 with the plasma heads aligned in parallel and in clustering;

      Fig. 4 is a perspective view of a microwave feeding unit of the plasma head shown in Fig. 3;

      Fig. 5 represents schematical drawings of the microwave feeding unit of Fig. 4;

      Fig. 6 represents a perspective view of an antenna to be used in the microwave feeding unit shown in Fig. 4 and  
20       a diagram to show propagation of microwave within the antenna;

      Fig. 7 represents a perspective view of an E-plane antenna of in-phase emission type and a diagram to show propagation of microwave within the E-plane antenna;

25       Fig. 8 is a plan view showing dimensions of a slot



plate of an H-plane antenna of in-phase emission type shown in Fig. 6;

Fig. 9 is a schematical drawing to show a procedure to calculate basic dimensions of the microwave feeding unit of the plasma head to be used in the microwave plasma CVD apparatus in an embodiment of the present invention;

Fig. 10 is a schematical drawing to show another procedure to calculate basic dimensions of a uniforming line of the microwave feeding unit of the plasma head to be used in the microwave plasma CVD apparatus in an embodiment of the present invention;

Fig. 11 represents drawings to show means for reducing the standing wave at the microwave feeding unit of the plasma head (longitudinal sectional view) to be used in the microwave plasma CVD apparatus shown in Fig. 1;

Fig. 12 is a drawing to show how to flow CVD gas at the plasma head of the microwave plasma CVD apparatus shown in Fig. 1 when CVD gas is passed by down-flowing in a plasma processing chamber;

Fig. 13 is a drawing to show the plasma head (longitudinal sectional view) of the microwave plasma CVD apparatus of Fig. 1 when CVD gas is passed by side-flowing in the plasma processing chamber; and

Fig. 14 represents a drawing and a diagram to show the plasma head of the microwave plasma CVD apparatus of Fig. 1, showing how to provide gas shielding.

5                   BEST MODE FOR CARRYING OUT THE INVENTION

Detailed description will be given below on embodiments of a microwave plasma processing method, a microwave plasma processing apparatus and a plasma head according to the present invention referring to the  
10 attached drawings.

[Microwave plasma CVD apparatus]

First, as shown in Fig. 1 and Fig. 2, in a microwave plasma CVD apparatus 1 in an embodiment of the present invention (hereinafter referred as "CVD apparatus of the  
15 present invention"), a substrate G (e.g. a glass substrate) is brought into a load-lock module 2 from a platform 6a or 6b and is sent to a process module 4 by a robot arm 3a via a transfer module 3 by a transport arm 2a. Then, linear plasma of high density is generated by  
20 a plasma head 5. Under the presence of the linear plasma, processing surface of the substrate (object to be processed) G is maintained at horizontal position with respect to the linear plasma, and plasma CVD processing is continuously performed on in-line basis on the  
25 substrate G. In particular, the plasma head 5 comprises

one or several plasma heads of the same type arranged in parallel and/or in clustering so that a plurality of different film-deposition processes can be carried out as to be described later (Fig. 3).

5        Here, the substrate G is transported by the robot arm 3a from the transfer module 3. It is then guided in the process module 4 by a guide rolls 9b and is placed on a substrate stage 9a arranged in a circulating endless substrate transport mechanism 9. Then, it is fixed by  
10 means such as an electrostatic chuck (not shown) and is moved in the process module 4, and CVD processing is performed by the plasma heads 5. After CVD processing, the substrate G is separated from the substrate stage 9a and is moved from the end of the process module 4 to the  
15 next processing stage. The emptied substrate stage 9a is brought back to the starting end of the process module 4 by the endless substrate transport mechanism 9. Under the endless substrate transport mechanism 9, a gas unit 7 and a cooling water unit 8 are provided.

20    [Plasma heads]

Plasma heads to be used in the microwave plasma CVD apparatus in the embodiment of the present invention comprise a plurality of unit plasma heads. For instance, three units 5a, 5b, and 5c are arranged in parallel via  
25 partition walls (not shown) as shown in Fig. 3.

Different types of processing are carried out by different types of film-deposition gases on the substrate G placed on the substrate stage 9a under the atmospheric pressure (normal pressure) or a pressure near the atmospheric pressure. For instance, as shown in Table 1, film-deposition process by a gas for depositing  $\text{Si}_3\text{N}_4$  film is performed at the plasma head 5a. A film-deposition process by a gas for depositing a-Si film is performed at the plasma head 5b, and a film-forming process by a gas for forming  $\text{n}^+\text{Si}$  film is performed at the plasma head 5c. As a result, three different types of film layers are formed on the surface of the substrate G.

To the plasma heads 5, the microwave feeding unit 50 as shown in Fig. 4 is applied.

15

Table 1

Film gas	Process gas	Cleaning gas	Carrier gas
$\text{n}^+\text{Si}$ process	$\text{SiH}_4\text{PH}_3$	$\text{NF}_3$	Ar or He
a-Si process $\text{Si}_3\text{N}_4$ process	$\text{SiH}_4\text{NH}_2$ $\text{H}_2$	$\text{NF}_3$	Ar or He
Bank material water repellent processing Direct Oxidation	$\text{F}_2$ , $\text{O}_2$	$\text{NF}_3$	Ar
Stage cleaning	-	$\text{NF}_3$	Ar

The microwave feeding unit 50 as shown in Fig. 4 is incorporated in the plasma head 5, and it fulfills the

functions as microwave-excited atmospheric pressure linear plasma generating unit. (In Fig. 4, it is shown upside down to more clearly indicate the structure.)

As shown in Fig. 5, the microwave feeding unit 50 is  
5 used to form linear plasma by using microwave. It comprises a waveguide 51 serving as an H-plane slot antenna or an E-plane slot antenna and a uniforming line 52. Between the waveguide 51 and the uniforming line 52, a slot array (slot plate) 51c is provided, which  
10 comprises a plurality of slots 53. The slot plate 51c comprises, as shown in Fig. 6, a plurality of slots 53 arranged alternately to left and right from the centerline of the waveguide 51 at a pitch of  $1/2$  of the guide wavelength  $\lambda_g$  in case of H-plane antenna. A slit  
15 55 is formed at a microwave emission end 54, which is the end of the uniforming line 52, and the unified microwave is emitted from the slit 55.

On the uniforming line 52, spatially more unified wave front of microwave is formed by using microwave with  
20 equal phase as emitted from the slot plate 51. This uniforming line 52 is a parallel flat line. More concretely, it is a flat rectangular waveguide with the centerline as the longer axis. By this uniforming line 52, microwaves discretely emitted from each of the slots 53  
25 are unified. A wave front with more uniform intensity is

prepared to the direction of the centerline, and the unified microwaves are emitted into plasma through the slit 55.

In particular, as shown in Fig. 5 (a) and Fig. 5 (b),  
5 the uniforming line comprises H-plane or E-plane antenna of the microwave feeding unit 50 used in the CVD apparatus of the present invention. The dimension from the slot plate 51c of the uniforming line 52 to the emission end 54 of the microwaves is designed as  $n \cdot \lambda_g/2$   
10 (where  $\lambda_g$  is guide wavelength, and  $n$  is an integral number), and the width is calculated as  $\lambda_g/2$ . The uniforming line 52 is made of dielectric substance such as  $\text{Al}_2\text{O}_3$  or AlN or quartz or a gas (a gas to make up a gaseous space). At the emission end 54 of the microwaves,  
15 a fluoride protective film 54a is coated. The waveguide 51 is made of a dielectric substance such as  $\text{Al}_2\text{O}_3$  or AlN or quartz or a gas (gaseous space).

As shown in Fig. 6 (b), on the H-plane antenna of in-phase emission type, an in-phase electric current flows  
20 from the centerline at a pitch of  $\lambda_g/2$  as shown in the figure. At the centerline, electric field is turned to nearly zero. Thus, at points with relatively high electric field (offset from the centerline by a distance "d"), slots 53a are formed alternately on both sides of  
25 the centerline on the waveguide 51a as shown in Fig. 6

(a). In this case, a distance from the final end of the waveguide 51a to the middle point of the slot 53a at the end is set to  $\lambda_g/2$ .

In case of the E-plane antenna, the slots 53 are  
5 formed on a waveguide resonator 51b with a spacing of  $\lambda_g$  along the centerline as shown in Fig. 7 (a) and Fig. 7 (b).

Fig. 8 is a plan view of the slot plate 51c of the H-plane antenna with the above arrangement.

10 Description will be given on another example of calculation to calculate basic dimensions of the uniforming line 52. As shown in Fig. 9,  
(Formula 1)

15 
$$\lambda_g = \frac{\lambda}{\sqrt{1 - \left(\frac{\lambda}{\lambda_c}\right)^2}}$$

where

20  $\lambda$ : Free space wavelength  
 $\lambda_c$ : Cut-off wavelength  
 $\lambda_g$ : Guide wavelength  
 $\lambda_c$ :  $2a$   
a: Width of waveguide  
25 b: Height of waveguide

The length  $l$  of the uniforming line 52 is basically set to the range of  $\lambda/4$  to  $3/4\lambda$ . The value is

determined by simulation. In this calculating procedure, calculation is made by using free space wavelength  $\lambda$ , and not using the guide wavelength  $\lambda_g$ . Similarly, calculation is made by setting the width of the  
5 uniforming line 52 as  $\lambda/2$ .

Further, as shown in Fig. 10, in case of the unified slit 52, which comprises quartz C on the slit 55 side and with atmospheric air A interposed between the slot 53 and the quartz C, the free space wavelength  $\lambda$  (quartz) in the  
10 atmospheric air is determined as follows:

(Formula 2)

$$15 \quad \lambda (\text{quartz}) = \frac{\lambda (\text{atmospheric air})}{\sqrt{\epsilon}}$$

where

$\lambda$ : Free space wavelength

$\epsilon$ : Dielectric constant

20 By applying calculation ratio of each component as shown in Fig. 10, wavelength after wavelength reduction in case of quartz ( $\epsilon = 3.58$ ) is calculated. The results are as shown in Table 2.



Table 2

	Dielectric constant $\epsilon$	Wavelength $\lambda$	$0.75 \lambda$	$0.13 \lambda$	$0.62 \lambda$
Atmospheric air	1	122.4 mm	91.8 mm	16 mm	-
Quartz	3.58	64.7 mm	48.5 mm	-	40 mm

Further, in order to eliminate the difference in  
 5 intensity distribution of the microwaves at the plasma  
 head due to the standing wave, a procedure for reducing  
 the standing wave is applied on the uniforming line 52.

In this procedure to reduce the standing wave, the  
 space of the uniforming line 52 is filled with a material  
 10 such as alumina ( $\text{Al}_2\text{O}_3$ ) with high dielectric constant to  
 shorten the wavelength. In this case, the length  $l$  of the  
 uniforming line 52 is turned to:  $\lambda$  (free space  
 wavelength) multiplied by an integral number, i.e.  $l = n \cdot$   
 $\lambda$ .

15 Also, as shown in Fig. 11 (b), the end of the  
 uniforming line 52 is extended by a distance of  $1/4 \lambda$ .

Further, as shown in Fig. 11 (c), an electromagnetic  
 wave absorbing material with high dielectric loss (such  
 as dummy load or water) is attached on the end of the  
 20 uniforming line 52 to absorb the electromagnetic wave.

Also, for the purpose of preventing abnormal

discharge (sparking) due to the increase of microwave output on the slot and of avoiding the crack of the dielectric substance in the uniforming line 52 due to local temperature increase, the slot plate 51c is made of  
5 a rigid metal plate of 3 to 5 mm in thickness as shown in Fig. 10, and the slot plate 51c is separated from the dielectric substance C made of a material such as quartz, alumina, etc. with atmospheric air space A interposed between them.

10 [How to pass CVD gas]

To pass CVD gas for film deposition in the microwave plasma CVD apparatus of the present invention, the following two methods are used: (1) gas down-flowing method, and (2) gas side-flowing method.

15 (Gas down-flowing method)

According to the gas down-flowing method, as shown in Fig. 12, the plasma head 60a comprises a waveguide 61a, a spacer 64a, a base flange 71a, a pair of exhaust ports 73a connected to the base flange 71a, and electrodes 69a  
20 mounted on the substrate G. A slit plate 62a is provided between the spacer 64a and lower end surface of the waveguide 61a. Also, a window 63a is arranged between the spacer 64a and upper end surface of the base flange 71a via a pair of O-rings 65a. Further, a spacer 67a is  
25 arranged under the window 63a, and a gas feeding nozzle

66a with a diluting gas exhaust port "a" and a raw gas exhaust port "b" is disposed in the spacer 67a (a uniforming line). Then, a film-forming gas comprising the diluting gas (e.g. Ar, He) and a raw material gas (e.g. SiH<sub>4</sub>) is blown down toward film-forming surface of the substrate G through the exhaust ports "a" and "b" as shown by arrows.

As the result of the gas down-flowing, the film-forming gas flows to a portion with high plasma density, and this extensively improves film forming rate. This is also helpful to maintain homogeneousness of the film-forming gas, and the attachment of the remaining substances to the gas feeding nozzle can be prevented.

(Gas side-flowing method)

According to the gas side-flowing procedure, as shown in Fig. 13, a plasma head 60b comprises a waveguide 61b, a spacer 64b, a base flange 71b, a converting flange 72b, a pair of gas feeding ports 75b connected to the base flange 71b, an exhaust port 73b, and electrodes 69b mounted on the substrate G. A slit plate 62b is provided between the spacer 64b and lower end surface of the waveguide 61b. Also, a window 63b is provided between the spacer 64b and upper end surface of the base flange 71b via a pair of rollings 65b. A spacer 67b (a uniforming line) is arranged at lower end of the window 63b. Further,

a head 76b in triangular shape is provided in a plasma chamber prepared between the lower end surface of this spacer 67b and the substrate G. Then, a diluting gas (e.g. Ar, He) is supplied through an exhaust port "a" of the gas feeding port 75b into the plasma chamber, and a raw material gas (such as  $\text{SiH}_4$ ) is supplied through another injection port "b". A film-forming gas is prepared by mixing these two types of gas, and the gas flows along the surface of the head 76b toward the substrate G as shown by arrows, and (side-flow) film forming is carried out. Then, the gas is exhausted to exhaust system through an exhaust port 73b. In this case, by changing the area of a flat surface 77b of the head 76b, film forming rate and film-forming condition can be adjusted.

By this side-flowing of the gas, homogeneity of the film-forming gas is improved, and exhaust operation can be promoted. Also, this makes it possible to predict the conditions on the film-forming surface and to facilitate the cleaning of the plasma head. Also, the width of the film formed on the substrate can be controlled by adjusting the shape of nozzle tip of the gas feeding port. (Gas shielding)

On the plasma head 60 of the microwave plasma CVD apparatus of the present invention, gas shielding is provided as shown in Fig. 14.

Specifically, as shown in Fig. 14 (a), a vacuum exhaust pipe 82 is mounted on the spacer 64 arranged on the lower end of the waveguide 61 of the plasma head 60. also, shield gas feeding pipes 83 and 83 to feed  $N_2$  and Ar gases etc. are connected to the converting flange 72 arranged on the lower end of the spacer 64 to form the plasma processing chamber with electrodes 69. Then, resistance plates 81 and 81 for providing unified feeding of the shield gas ( $N_2$ , Ar) toward downstream side are mounted. Further, resistance plates 80 and 80 for performing homogeneous exhaust of the film-forming gas supplied from the gas feeding nozzle 66 in the plasma processing chamber are arranged on the exhaust end of the film-forming gas.

Then, as shown in Fig. 14 (b), it is designed in such manner that a pressure  $P_1$  (pressure in the plasma processing chamber; e.g. pressure in the range between normal pressure and 1 Torr),  $P_2$  (pressure near the resistance plate), and  $P_3$  (pressure on the outermost periphery of the plasma head) are to be in the relation of  $P_1 < P_3 < P_2$ . Then, walls of pressure (pressure peaks) develop between the sites, and this prevents the leakage of the gas from the film-forming processing chamber, and perfect gas shielding can be provided.

25